Tsunami Inundation Visualization

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Abstract

Numerical simulations conducted by researchers at the University of Washington are used to model and predict the impact of tsunamis. By estimating the probability of occurrence of each simulated tsunami, the probability of exceeding a given level of inundation (flooding) can be estimated for every point in the landscape, giving rise to a hazard map. Visualizing hazard maps is difficult for several reasons. First, the data has a large amount of uncertainty: the probability of each simulated event must be estimated, and the hazard maps are also generated from a limited pool of simulated events, thus they may not account for the worst or most exotic tsunamis. Second, the resultant hazard maps specify a complex hazard function at every point, which describes the probability of inundation at every depth.

To effectively communicate the dangers and potential impacts of tsunamis to the general public, we employ interactive and research-driven design techniques to enhance users' understanding of the complex data. We display contour plots of inundation level for fixed probabilities, and allow the users to manipulate the probabilities to see how inundation changes over the landscape. We additionally use small multiples to present the user with an overview of the inundation from a sample of individual simulations, showing the possible variety of outcomes over separate events. Our hope is that by showing both the aggregate data and the data for individual simulations, we can reduce the level of abstraction in the uncertainty measures that are typically reported. To further improve user comprehension of our data, provide context, and generate interest we embed our visualizations in an article-style narrative structure.

1 Introduction

Coastal cities along the West Coast are particularly susceptible to damage caused by tsunamis. For the scope of this project, we focus on *Crescent City*, a coastal town in California which has a history of extreme damage from tsunamis. To improve Crescent Citys preparedness going forward, researchers seek to better understand the impact of tsunamis arising from a number of possible seismic events. One approach is to use numerical simulations to predict tsunami damage. The process of modeling a tsunami begins with the specification of the seismic event causing the tsunami. This entails stipulating a slip pattern, which measures where and to what degree the ocean floor moves in during the earthquake, and the location of the earthquake. The slip pattern determines how water is displaced, leading to the initial formation of the tsunami. The virtual tsunami is then tracked from the epicenter of the seismic event, across the ocean, and to the Crescent City harbor to determine the degree of inland flooding, known as inundation.

We have been given data from a set of 13 numerical simulations. Each simulation corresponds to a single seismic event and yields predicted inundation levels in a 250×250 grid centered over Crescent City harbor (at approximately (41.7558,-124.2026) in decimal degrees (DD)). Associated with each seismic event is the *annual probability* of the event occurring. We have also been provided experts' best estimates of these probabilities. For simplicity, researchers typically assume that earthquakes are independent. However, there is likely some correlation between seismic events (e.g. one would not expect two large earthquakes to occur in a row, but smaller aftershocks are quite common). Note that it is not uncommon for scientists to have access to only a small number of simulated events, since the simulations are expensive to run. Seismic events as far away as Asia can induce tsunamis that strike the West Coast. To simulate damage from such events, one must propagate the resulting tsunamis across the entire ocean and into Crescent City harbor. Doing so accurately makes these simulations extremely computationally costly.

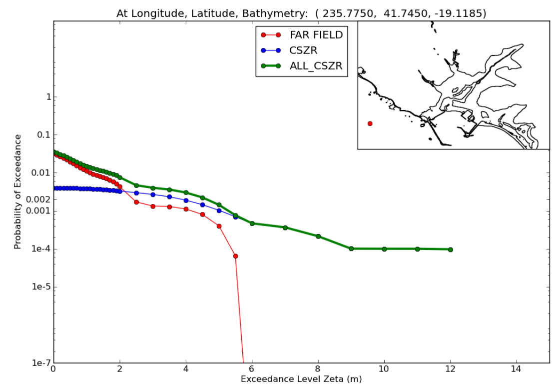

Figure 1: Three hazard curves, each corresponding to a different subset of the numerical simulations. The spatial point whose hazard curves are plotted is shown as a red dot in the map in the upper-right.

There are three types of visualizations that are typically used to convey the results of tsunami simulations. For this project we focus on the following.

Given the annual probability of each simulated tsunami and fixing a point on the grid we can compute the annual probability of water exceeding any particular level of inundation. Allowing the inundation level to vary, we can construct what is known as a *hazard curve*: a one-dimensional curve showing the predicted annual probability of the water reaching different levels at a fixed point in space. Figure 1 shows a set of three hazard curves, each corresponding to a different subset of the numerical simulations. The annual probability is plotted on the y-axis and the inundation level (or exceedance level) is plotted on the x-axis.

Fixing an annual probability, allowing the spatial point to vary, and plotting the associated inundation levels from the hazard curves, we obtain a *hazard map*. Figure 2 provides an example of a hazard map generated by the research team with which we collaborated on this project. One of the team's goals is to effectively communicate their findings to the general public. However, accurately interpreting hazard maps and their siblings can be challenging for people without

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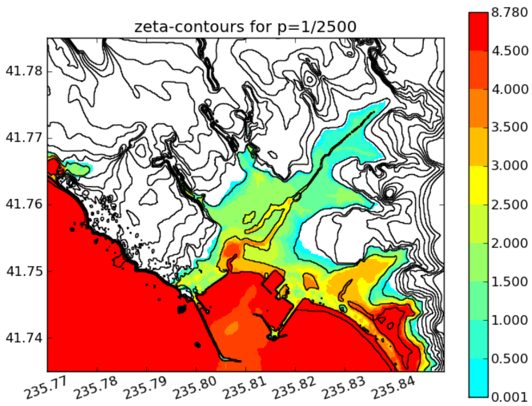

Figure 2: A hazard map for the Crescent City harbor area with annual probability set to $p = 1/2500$. The inundation level has been encoded via color.

Furthermore, there are multiple *sources of uncertainty* (both aleatoric and epistemic) that feed into hazard maps:

1. Estimation of annual probability of different seismic events;
2. Variability of outcomes over a small number of events;
3. Error due to the assumption that the seismic events are independent;
4. Error in the numerical simulations of tsunamis.

Researchers would especially like to be able to communicate the uncertainty inherent in tsunami simulations to a general audience.

Our goals for this project are twofold. First, we would like to present hazard maps in a manner that is easily intelligible for non-experts. Second, we seek to convey the uncertainty underlying hazard maps in an intuitive way.

The remainder of this report is organized as follows. We give an overview of related work from the data visualization community in Section 2. In Section 3 we discuss the methods employed to address the problems stated above. We present some preliminary results in Section 4 and discuss insights drawn from them in Section 5. Finally, we describe how our work could be extended and/or improved in Section 6.

2 Related Work

Prior to our work with the data, the outcomes of these simulations for Crescent City were communicated in the technical report [1]. Typical visualizations in this work look similar to Figure 2, and the report is geared towards a technical audience. One of our main goals is to extend these visualizations to be accessible to a wider audience, with a less rigorous statistical background.

Much work has been done on improving visualizations involving uncertainty, but there is still no consensus within the field on best practices, and the appropriate techniques often depend on the context (e.g. audience type, uncertainty type).

Hypothetical outcome plots (HOPs) were introduced in [3] as a way to help viewers of a visualization understand the uncertainty inherent in the data being presented. The authors advocate for representing probability distributions using animations cycling through a finite set of discrete possible outcomes, rather than static tools such as error bars or violin plots. HOPs were shown to outperform error bars and violin plots for judgments about plots of two and three quantities. HOPs were designed in particular for communicating information about probabilities to audiences with limited statistical backgrounds. Follow-up work in [2] established that ”visualizing uncertainty as a set of discrete outcomes, as opposed to a continuous probability distribution, could improve recall of a sampling distribution from a single experiment.” We draw on HOPs as inspiration for the flipbook part of our visualization (details in Section 3.2).

3 Methods

Our visualizations are implemented in HTML and JavaScript using the D3 framework. The maps in our visualization are built using the Google Maps API. Throughout, inundation levels are overlaid on the maps as shaded contour plots, with color encoding water depth above normal (meters). We select a color palette with colors that are distinguishable for every type of color-blindness. Dark blue and purple intuitively correspond to deeper water and yellowish greens to milder levels of flooding.

We employ a number of techniques to achieve our two goals.

3.1 Narrative

Rather than present our visualizations in a vacuum, we embed them within a larger narrative structure to make them more digestible. In particular, we adopt the “magazine style” approach of Segel and Heer [4]. We begin with an anecdote that emphasizes the usefulness of numerical simulations to grab the reader’s attention. Preceding each visualization is a short body of text explaining both the rationale behind showing the visualization and providing information to prime the reader so that they can more effectively interpret the visualization. Following each we provide some useful observations to help ensure readers do not miss out on any insights we think they should make. The narrative format of our web page, paired with the interactivity of our visualizations, guides readers’ thinking through the complexities of probabilistic hazard mapping while allowing them the flexibility to explore the data and draw their own conclusions.

3.2 Flipbook

The first visualization piece we present to viewers is a flipbook-style animation which rotates through the full set of 13 simulations, showing the effects of each on the map. The flipbook was inspired by the sampling-based visualizations of uncertainty at the Interactive Data Lab at the University of Washington [2]. Seeing the results of all the simulations gives the viewer an implicit introduction to the variability present in the data. We have a relatively small number of simulations (13), many with very different outcomes, and the likelihood of each event can vary by orders of magnitude. In order to show a range of possible events including the most extreme simulations (rather than, say, showing simulations at rates proportional to their annual probabilities), we postpone considerations of the likelihood of each event for the aggregate maps and probability explorer to follow. We include a silhouette of a person of average height beside the legend to give readers unaccustomed to reasoning in meters (the unit used in the simulations) a better idea of the scale of the flooding depth.

3.3 Small multiples

Moving on to our main visualization and delving deeper into the specifics of the data, we use small multiples of six simulations at a time to simultaneously convey a broad range of possible outcomes in the event of a tsunami. Showing specific events highlights the variety of possible outcomes, ensuring that extreme events are not lost in the aggregate map. The small multiples also allow the reader to make direct comparisons between simulations, which is difficult to accomplish using the flipbook. Labels describe the plotted seismic events and give annual probabilities for each, providing additional context. They are also shown directly beside an aggregate inundation map to facilitate further comparison and encouraging users to observe how different simulation results factor into the aggregate map.

3.4 Aggregate inundation map

While it can be fruitful to examine the results of individual simulations, for this information to be actionable readers need a way to consolidate outcomes from all the simulations. This is accomplished by combining the results of individual simulations into an aggregate hazard map, shown to the left of our small multiples visualization. The aggregate map shows expected inundation level over all simulated events for a fixed probability. Users can interact with this map by panning, zooming, and pinpointing areas of interest. Selecting an area pans and centers the small multiples plots to to the same location so that simulation results in areas of interest can be examined more closely. A slider allows users to vary the probability threshold used to create the map.

For both the aggregate map and small multiples, users can also choose to filter the simulations that are shown based on the type of seismic event modeled: near-field (Cascadia subduction zone), far-field (other origin) events, or both. These sets of events vary in severity and likelihood.

3.5 Interactive probability explorer

Often users are concerned with the likelihood of a tsunami over a number of years, not the probability one will occur in the next year. For example, one might wonder: over the 30 years I expect to live in this house, what are the chances I will experience significant flooding due to a tsunami?

Going from the annual probability of an event (or collection of events) to the probability over a number of years is slightly nuanced. To mitigate user confusion about annual probabilities and to help users reason effectively about long-term risks, we provide an interactive probability explorer. This explorer allows readers to enter an annual probability, p, and a number of years, N. It then returns the probability that at least one event (or collection of events) with annual probability p will occur over a period of N years. The interactive nature of the calculator allows users to enter annual probabilities from simulations that stood out to them from the small multiples graphic or from the hazard map and more accurately compute the likelihood of such events over time.

4 Results

Here we present the visualizations produced for our project. Dynamic versions can be found on our project website. All visualizations are embedded in an article-like web page. A static version of the flipbook visualization described in Section 3.2 is shown in Figure 3. Each simulation image is shown for about two seconds before fading out and a new run fading in. The combined hazard map and small multiples visualization is given in Figure 4. In this image the user has clicked on the point enclosed by the red circles in the seven plots, causing the small multiples maps to shift their centers from the default position to this point. Figure 5 illustrates how our probability explorer from Section 3.5 functions.

5 Discussion

Users who have read through our article should have an increased understanding of tsunami simulations and the uncertainties behind them, be able to interpret tsunami hazard maps, and be capable of working the annual probabilities of sets of events into the decision-making process.

Users unfamiliar with the topic had the following insights:

- Lots of uncertainty surrounding whether actual earthquakes will resemble those that were simulated. The simulated ones have very low estimated probabilities of occurring. (Andreas)

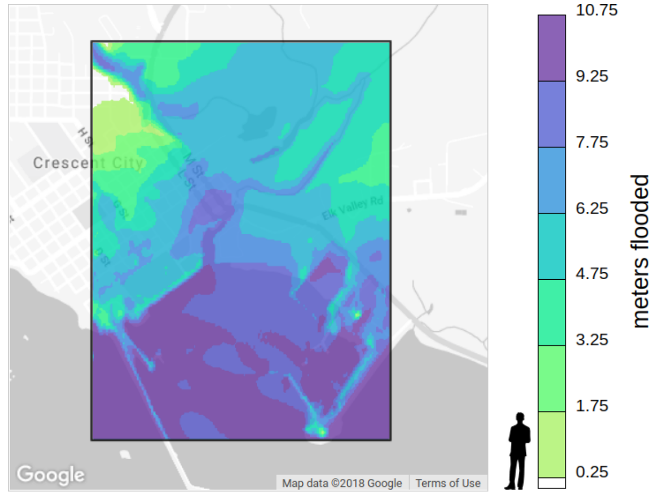

Figure 3: A static image of our flipbook animation.

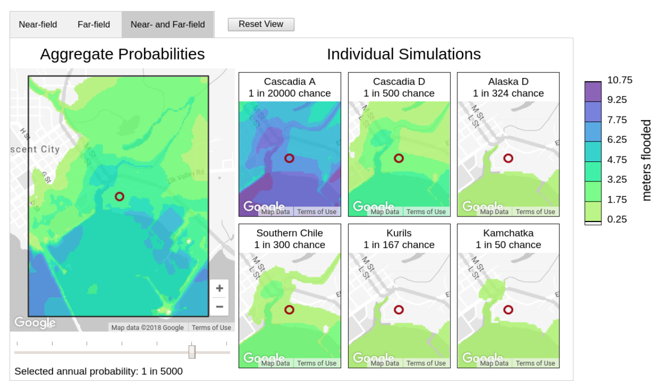

Figure 4: An aggregate inundation map beside small multiples of some of the simulations used to construct it

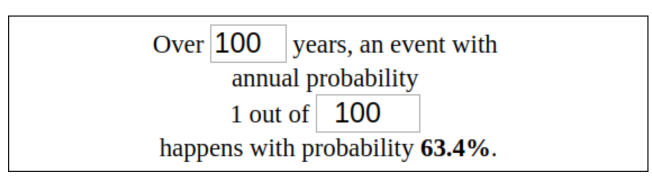

Figure 5: Our probability explorer

6 Future Work

"A description of how your system could be extended or refined. We have read papers from a number of conferences throughout the course, but if you are having trouble figuring out how to write your paper, take a look at representative papers from the conferences listed above."

There are a number of ways that the current work could be extended:

- With additional simulations, the map could cover a greater geographic region, including additional cities,
- Additional simulations also reduce uncertainty and give a better sense of possible outcomes,
- By using alternative encodings of uncertainty, results may be made more readily interpretable. In addition, it would be interesting to evaluate the usefulness of the interactive probability explorer in a controlled study with human subjects.

Due to the importance of estimating the hazards posed by tsunamis for evacuation and other emergency planning, FEMA and the State of California funded the research of [1] that produced the simulations used in these visualizations. Crescent City was the focus of their project, where the inundation and probabilistic contour maps developed were strongly encouraged as "a product that supplements and aids in the practical interpretation of the same probabilistic information displayed in the standard 100- and 500-year tsunami maps." Many studies have demonstrated that interpreting static visualizations that convey uncertainty can be challenging. Static visualizations produced by the government that serve as warnings to homeowners and residents in Crescent City and other coastal cities would benefit from the tools of LeVeque et. al. and recent uncertainty visualization research. Future work would include developing similar probability and inundation contours for Washington State and determining which of the techniques presented here and in the literature would be most beneficial for public safety and preparedness.

Acknowledgments

We would like to thank Professor Randy LeVeque for suggesting the project and for the providing the data that went into the tsunami simulations. The techincal report and Github repository were invaluable tools in our effort to complete this project. We would also like to thank Professors Ann Bostrom and Dan Abramson for their helpful discussions and Professor Heer and Halden for their feedback during the milestone review.

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